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Steady-State Analysis and Voltage Control of Self-Excited Induction Generator (SEIG)

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Abstract— **Self-Excited Induction Generators have become the prime choice for wind energy conversion in remote and rural areas due to many advantages over Grid Connected Induction Generators. However, their main drawback is poor voltage and frequency regulation. Steady state analysis for such machines is important to understand their behaviour under varying operating conditions.In this paper steady-state performance of SEIG (with general RL load) under varying operating speed, excitation capacitance and load is presented using a simple and fast nodal analysis and piecewise linearization of magnetization characteristics. Moreover, terminal voltage control of SEIG by means of capacitor switching is investigated. MATLAB is used to simulate the analysis and the conformity between simulation results and other research papers in this field validates the theoretical approach presented in this paper.**

Keywords-component; Self-excited induction generator; Steady-state analysis; Nodal analysis; Magnetization characteristics; Voltage control; Capacitor switching.

I. Introduction

Over the past decades, the world has come to an understanding that burning of the fossil fuels for electricity generation may not the best and most efficient solution considering the ever growing fuel costs and environmental hazards it poses such as global warming. Furthermore, fast depletion of these resources and political dependency that it brings upon the nations with least reservoirs of such resources, urged politicians and researchers to look for new sources of energy. Over the past few years, wind energy had the fastest growing rate compare to the other renewable sources of energy. Due to extensive R&D effort done in this field, “the life span of modern wind turbines is now about 20-25 years, which is comparable to many other conventional power generation technologies” [1]. Wind energy has proved to be very economical compare to other renewable energies such as solar and tidal, since by recent technological development and increase in installed capacity and production level, the average cost of electricity generation has declined [1].

Fixed Speed wind power generating systems have gained much popularity among the manufacturers and developers in this field mainly due to the fact that fixed speed wind turbines choice of generator is Squirrel Cage Induction Generator [2]. Unfortunately, the main drawback of this generator is that instead of generating reactive power it absorbs reactive power required for real power generation. Therefore, researchers have proposed 2 methods to provide required reactive power for Induction Generator, namely: 1) Grid Connected Induction Generator (GCIG) and-2) Self-Excited Induction Generator (SEIG). In Grid Connected Induction Generator (GCIG) configuration, the generator draws its reactive power from the grid. [3, 4, 5] have in detailed explained the principal operation of Grid Connected Induction Generator. Another method for providing reactive power required for generator magnetization is by connecting VAR generating units in the form of capacitor banks across its stator terminals. This method eliminates the need for a power grid. One of the advantages of this configuration is that since, it does not require the grid for operation; hence, it is suitable for standalone operation such as in rural areas and isolated places. That is why it is also called the “Standalone Induction Generator” or “Autonomous Generator”. Fig1 shows SEIG configuration.

When the capacitor banks are connected across the stator terminals of an Induction Generator and the Induction Generator is driven externally by a prime mover, the capacitor banks can provide the magnetizing requirement of the Induction Generator. Initially, when the motor first starts to run, the residual magnetism in the rotor circuit will induce a small emf across the stator terminals. If the induced emf is sufficient, it will produce a capacitive (leading) current flow. The magnetic flux produced by these currents will further assist the residual magnetism in the rotor circuit leading to larger induced emf. This in turn increases the capacitive currents and resulting flux. The induced voltage and capacitive currents continue to rise until the machine reaches the saturated state [1]. At this operating point, the voltage and current continue to oscillate at a given peak value and frequency. Therefore, for Self-Excitation to occur these conditions are necessary: 1) there should be sufficient residual magnetism in the rotor circuit. Without residual magnetism in rotor no voltage will build up. 2) The capacitor banks should be of sufficient value. Al Jabri & Alolah [6] calculated the minimum value of capacitance required for Self-Excitation to occur under no load condition and for a general resistive-inductive load. They have used a simple and direct method to solve two nonlinear equations in contrast with different numerical methods which were known from the previous works in this field. The main drawback of Self-Excited Induction Generator compare to the Grid Connected Induction Generator is that due to absence of the grid, the generated frequency and voltage are no longer set by the grid instead they are dependent on factors such as load, capacitance and prime mover speed. Therefore, with any variation in these factors they no longer remain constant. It is proven, that the terminal voltage of SEIG falls sharply with the application of generator loading, and frequent variation of speed which is the character of wind turbines results in poor performance of frequency and terminal voltage which means poor power regulation in the absence of regulating techniques [7].

Steady-state analysis of Self-Excited Induction Generator is of vital importance both for designing and observing the behavior of isolated Induction Generator. Since in this mode of generation, terminal voltage and frequency are unknown and depend on prime mover speed, terminal capacitance and load, it is essential to perform the steady-state analysis on such a machine in order to observe its behavior under varying conditions and designing accordingly. In the case of Grid Connected Induction Generator, the voltage and frequency is known and the machine is operating at the rated operational point, therefore the magnetizing reactance of the machine is constant and can take one value which is the rated magnetizing reactance. But the main complexity arises here in the case of SEIG, because the magnetizing reactance of the machine is not constant and varies considerably with the terminal voltage and frequency. A number of papers have performed the steady-state analysis of Self-Excited Induction Generator. [2, 1] used the d-q model to investigate the steady-state performance of SEIG. Vadhera & sandhu [8] performed the steady-state analysis with the aid of Genetic Algorithm (GA), Pattern search (PS) and Quasi-Newton optimization tools in MATLAB. Though, these methods are very accurate, but their complexity limits their usage. Joshi et al. [9] have used iterative technique to find the generated frequency during steady-state operation of SEIG and Artificial Neural Network (ANN) to replace the piecewise linear approximation of nonlinear Magnetizing reactance of Induction Generator. While, Artificial Neural Network is proved to be more accurate in capturing the magnetizing behaviour of Induction Generator than piecewise linear approximation, but using iterative technique to find generated frequency is time consuming and to some extent inaccurate. Dimitrov & Mutaftchiev [10] have presented a very simple method to perform the steady-state analysis of SEIG by considering the per phase equivalent circuit of SEIG as a series resonating circuit. The most simple and fastest method to perform steady-state analysis of SEIG is given by [2] in which nodal analysis is done on the per phase equivalent circuit of SEIG for a resistive load. The only drawback of this method is that it uses the piecewise linear approximation of nonlinear Magnetizing reactance of Induction Generator which is not as accurate as Artificial Neural Network (ANN). This paper is highly based on the latter method but for resistive and inductive loading.

Self-Excited Induction Generator is independent of the grid; therefore, it is free from synchronization problem and due the fact that its application is mostly in rural areas which, mainly resistive loads (frequency independent load) model their load behaviour, the slight variations in frequency is tolerable. In case of generator loading the frequency varied slightly and for the varying operating speed; though, frequency variation is considerable, but still not big enough to raise concerns. Therefore, the problem of voltage control is of the main priority. To control the terminal voltage of Self-Excited Induction Generator, [2] have recommended the use of *Wound Rotor* Induction Generator in order to facilitate the variation of rotor resistance. However, this method increases the cost as it is using Wound Rotor Induction Generator type and it needs special skills for operators. [8] Use the Genetic Algorithm (GA) to predict the value of excitation capacitance required to maintain the terminal voltage under any loading condition. Murthy et al. [11] have shown that excitation capacitance must be varied over a wide range to maintain the generator voltage constant. Capacitor Switching is cheap and simple solution to maintain terminal voltage constant. [12] proposed a new model based on their previous model for the steady-state analysis of SEIG to calculate the exact value of excitation capacitance for capacitor switching to maintain the terminal voltage. Other schemes such as thyristor controlled reactor [13] and thyristor controlled DC voltage regulator [14] can also provide constant voltage operation. Capacitor switching is a very simple and cheap method to maintain the SEIG terminal voltage within tolerable limit during the application of speed and load variation. In this paper simulations are done for the case of resistive-inductive (RL) load for both conditions of speed and load variation, to observe the efficiency of this method.

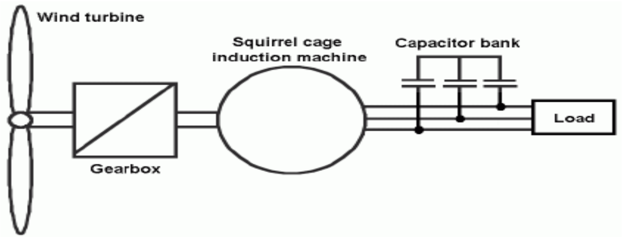

Figure1. Self-Excited Induction Generator (SEIG). [1]

II. Steady-State Equivalent Circuit Nodal Analysis

For the steady-state analysis the following assumptions have been made:

- All the circuit parameters, except magnetizing reactance $X_{m,}$ are assumed to be constant and unaffected by machine saturation.
- The core losses of the machine have been neglected.
- Inductive and capacitive reactance is computed at rated frequency (base frequency) $f_{b.}$

Per phase equivalent circuit of a Self-Excited Induction Generator with a resistive-inductive (RL) load is shown in figure 2. The per unit frequency here is shown by the symbol "a".

The circuit impedances are:

$$Z_{Rotor} = \frac{Rr}{s} + jaX_r \tag{1}$$

$$Z_m = jaX_m \tag{2}$$

$$Z_{Stator} = R_S + jaX_S \tag{3}$$

$$Z_C = -j\frac{X_C}{a} \tag{4}$$

$$Z_L = R + jaX \tag{5}$$

Load impedance and capacitive impedance are parallel, therefore:

$$Z_{tot} = Z_L \Big\| Z_C = (R + jaX) \Big\| (-j\frac{X_C}{a}) = \frac{(R + jaX)(-j\frac{X_C}{a})}{R + j(aX - \frac{X_C}{a})} \tag{6}$$

Multiplying both numerator and denominator with the conjugate of denominator gives:

$$\Rightarrow Z_{tot} = \frac{RXX_C - R\frac{X_C}{a}(aX - \frac{X_C}{a}) - j\left[XX_C(aX - \frac{X_C}{a}) + R^2\frac{X_C}{a}\right]}{R^2 + (aX - \frac{X_C}{a})^2} \tag{7}$$

Separating real and imaginary parts:
The real part is:

$$R_L = \frac{RXX_C - R\frac{X_C}{a}(aX - \frac{X_C}{a})}{R^2 + (aX - \frac{X_C}{a})^2} \tag{8}$$

The imaginary part is:

$$X_L = \frac{XX_C(aX - \frac{X_C}{a}) + R^2\frac{X_C}{a}}{R^2 + (aX - \frac{X_C}{a})^2} \tag{9}$$

The stator impedance is in series with Z_{tot}, therefore:

$$R_{1L} = R_S + R_L \tag{10}$$

$$X_{1L} = aX_S - X_L \tag{11}$$

Analysis at node 1 gives:

$$I_r = I_S + I_m \tag{12}$$

It can be re-written as:

$$\frac{E_a}{\frac{R_r}{s} + jaXr} = \frac{E_a}{R_{1L} + jX_{1L}} + \frac{E_a}{jaX_m} \tag{13}$$

Expressing equation (13) in Cartesian form:

$$\frac{sR_r - js^2aX_r}{R_r^{\ 2} + a^2s^2X_r^{\ 2}} - \frac{R_{1L} - jX_{1L}}{R_{1L}^{\ 2} + X_{1L}^{\ 2}} + \frac{j}{aX_m} = 0 \tag{14}$$

Equating real and imaginary parts of equation (14) with zero, gives:
The real part gives:

$$\frac{sR_r}{R_r^{\ 2} + a^2s^2X_r^{\ 2}} - \frac{R_{1L}}{R_{1L}^{\ 2} + X_{1L}^{\ 2}} = 0 \tag{15}$$

The imaginary part gives:

$$\frac{s^2aX_r}{R_r^{\ 2} + a^2s^2X_r^{\ 2}} - \frac{X_{1L}}{R_{1L}^{\ 2} + X_{1L}^{\ 2}} - \frac{1}{aX_m} = 0 \tag{16}$$

Rearranging equation (15) for slip, gives:

$$A_2s^2 + A_1s + A_0 = 0 \tag{17}$$

Where:

$$A_2 = a^2X_r^{\ 2}R_{1L}$$

$$A_1 = -R_r(R_{1L}^{\ 2} + X_{1L}^{\ 2})$$

$$A_0 = R_{1L}R_r^{\ 2}$$

Equation (17) gives the generator slip during steady-state operation with load and excitation capacitance known. Out of two values of slip derived from equation (17) only smaller one is feasible in generating mode [7]. Equation (18) can be used to find the operating speed which results in the desired generated frequency with load and excitation capacitance known.

$$v = a(1 + s) \tag{18}$$

Rearranging equation (16) for X_m, gives the formula to calculate magnetizing reactance for any operating slip of the generator with load and capacitance known.

$$X_m = -\frac{R_r(R_{1L}^{\ 2} + X_{1L}^{\ 2})}{sa^2X_2R_{1L} + aR_rX_{1L}} \tag{19}$$

Generally, the value of magnetizing reactance for a machine is found experimentally by performing the no-load test on the machine. For the machine chosen for this paper these values are given corresponding to the per phase air gap voltage at *rated frequency* by piecewise linear magnetization in appendix. With the value of magnetizing reactance known for a particular operating slip, the corresponding per phase air gap voltage at *rated frequency* E_1 can be found by using the machine piecewise linear magnetization characteristic. Multiplying E_1 with per unit frequency "a" gives the air gap voltage corresponding to the *current frequency* E_a. From there, the stator current, terminal voltage, load current, output power and etc… can be computed easily.

Stator current: $$I_S = \frac{E_a}{R_{1L} + jX_{1L}} \qquad (20)$$

Terminal voltage: $$V = I_S(R_L - jX_L) \qquad (21)$$

Load Current: $$I_L = \frac{V}{(R + jaX)} \qquad (22)$$

Output Power: $$P_O = VI_L \cos(\theta) \qquad (23)$$

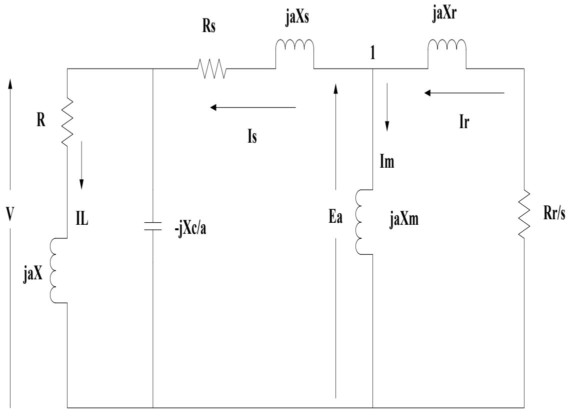

Figure2. Per Phase Equivalent Circuit of SEIG with RL load.

III. Simulation Results

Simulations are done on the machine chosen for this paper based on the method developed earlier. The machine parameters are given in the appendix.

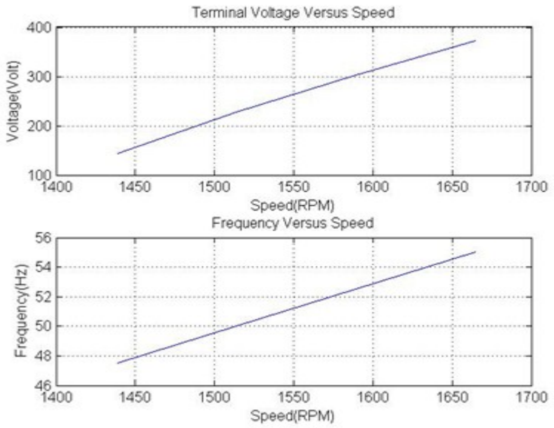

Figure3. Variation in Terminal Voltage and Frequency Vs. Operating Speed, R=1p.u. X=2p.u. C=65microFarad.

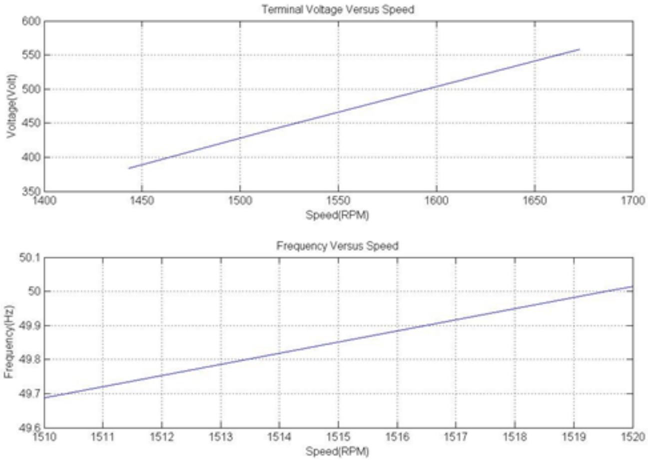

Figure4. Variation in Terminal Voltage and Frequency Vs. Operating Speed. R=1p.u. X=2p.u. C=100microFarad.

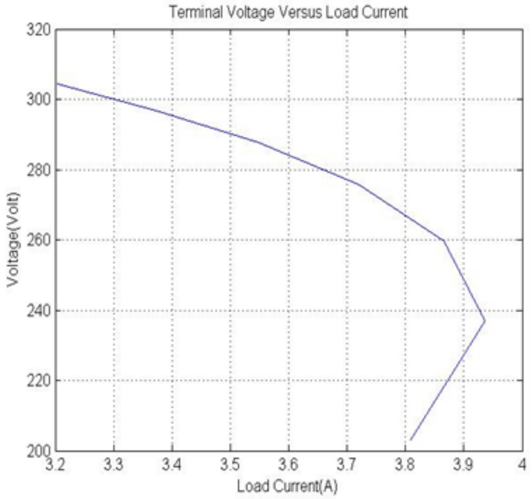

Figure5.Variation of Terminal Voltage with Resistive Loading. (C=52microFarad, Speed=1533 RPM)

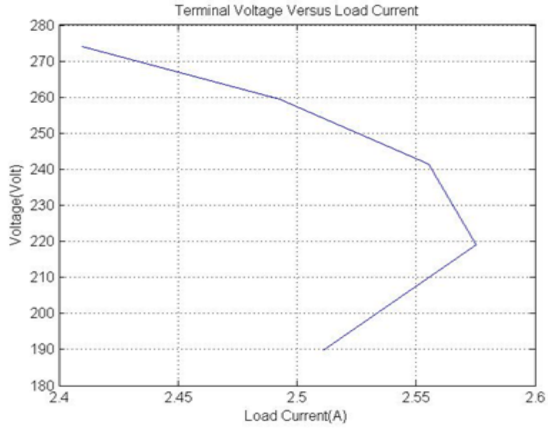

Figure6. Variation of Terminal Voltage with Resistive-Inductive (RL) Loading.(C=60microFarad, Speed=1533 RPM)

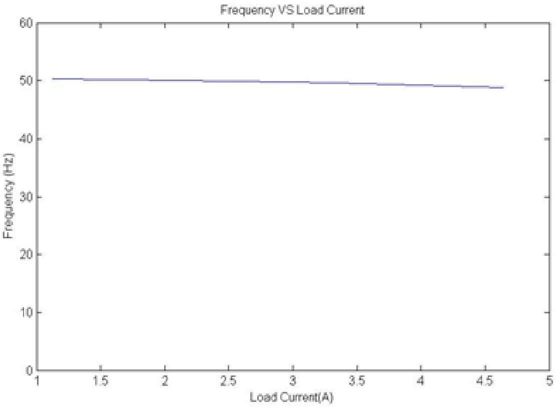

Figure7. Variation of Generated Frequency with Resistive-Inductive (RL) Loading. (Capacitance=70microFarad, Speed=1515 RPM)

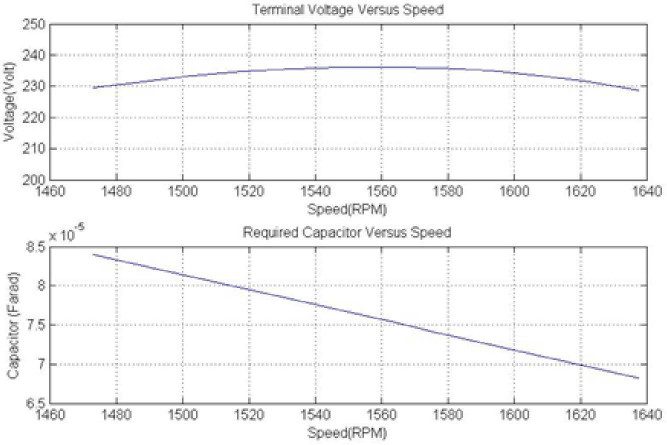

Figure9. Controlling the Terminal Voltage By Means of Capacitor Switching in Case of Speed Variation. (R=1p.u. X=1p.u.)

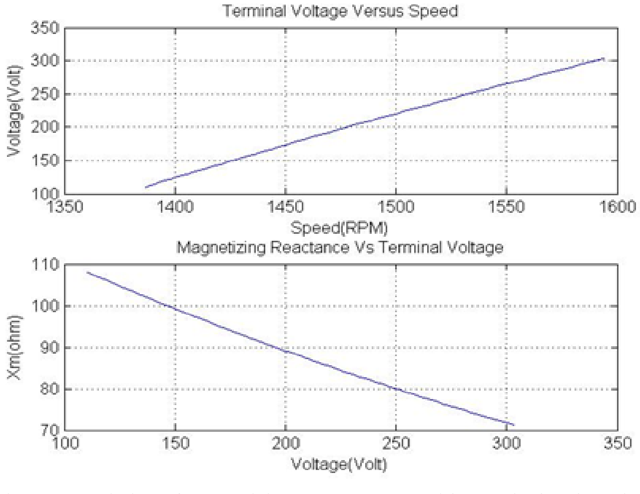

Figure8. Variation of Magnetizing Reactance X_m with Terminal Voltage in Case of Resistive-Inductive Loading. (R=1.5p.u. X=1.8p.u. C=62microFrad)

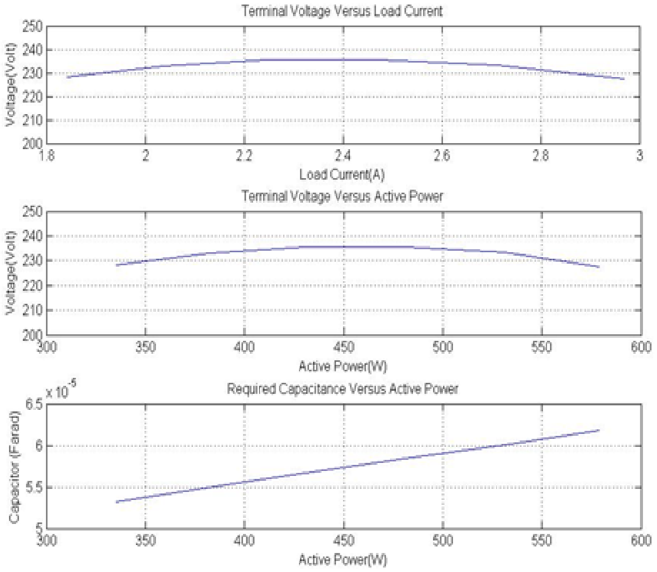

Figure10. Controlling the Terminal Voltage By Means of Capacitor Switching Case of Load (RL) Variation. (Speed=1515RPM)

IV. Conclusion

In this paper Steady-State analysis of Self-Excited Induction Generator was performed based on nodal analysis. This method is faster and simpler than conventional models used such as d-q model and Genetic Algorithm (GA). However, due to using piecewise linear magnetization curve, its accuracy is inferior to Artificial Neural Network technique (ANN). Variations of terminal voltage and frequency with operating speed, excitation capacitance and load were presented. It was shown that the generator's terminal voltage varies considerably with the application of speed variation and generator loading. The results shown that, the terminal voltage varies somewhat linearly with the operating speed and falls sharply in the case of generator loading. The fall of terminal voltage in case of generator loading, was observed to be even more severe during the inductive loading of the generator. This a serious problem associated with the Self-Excited Induction Generator and needs proper controlling schemes to keep the terminal voltage close to its rated value during the variation of operating conditions (wind speed and load). Capacitor switching provided simple, cheap and acceptable voltage control. Furthermore, it was seen that the frequency of the generator also, varies with operating speed and load current. However, this variation was seen to be negligible in case of generator loading and overall not a matter of concern due to SEIG application. The magnetizing behaviour of the machine during self-excitation was shown. The conformation between simulations and theory validated the results.

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Appendix

In this paper a 3-phase, 4 poles, 50 Hz Star connected Squirrel Cage Induction Generator with parameters listed in table 1 is used for simulations.

Table I. Machine parameters

Parameters	**Value**
Rated Power (*P*)	2.2KW/3.0 Hp
Rated Voltage (*V*)	415V (Phase-to-Phase)
Rated Current (*I*)	4.96 A
Stator Resistance (R_S)	3.35Ω/0.072p.u.
Rotor Resistance (R_r)	1.76Ω/0.038p.u.
Stator Reactance (X_S)	4.85Ω/0.1047p.u.
Rotor Reactance (X_r)	4.85Ω/0.1047p.u.
Rated Magnetizing Reactance (X_m)	83.25Ω/1.797p.u.
Base Impedance (Z_{base})	46.32Ω
Base Speed	1500 RPM
Base Frequency	50 Hz
Base Voltage	230 V (phase-to-neutral)

The piecewise linearization of magnetization characteristics of the machine chosen for this thesis is as follows:

$Xm < 82.292$	$E1 = 344.411 - 1.61Xm$
$95.569 > Xm \geq 82.292$	$E1 = 465.12 - 3.077Xm$
$108.00 > Xm \geq 95.569$	$E1 = 579.897 - 4.278Xm$
$Xm \geq 108.00$	$E1 = 0$